North Sea chalk - textural, petrophysical and acoustic properties

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Publication date:
2002

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Røgen, B. (2002). *North Sea chalk - textural, petrophysical and acoustic properties*. Environment & Resources DTU. Technical University of Denmark.

Environment & Resources
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Birte Røgen

North Sea chalk
- textural, petrophysical and acoustic properties

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Ph.D. Thesis, 2002
Environment & Resources DTU
Technical University of Denmark

North Sea chalk
– textural, petrophysical and acoustic properties

Cover: Birte Brejl
Printed by: DTU tryk
Environment & Resources DTU
ISBN 87-89220-63-3

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This thesis is submitted to the Technical University of Denmark as partial fulfillment of the requirements for obtaining the Ph.D. degree.

Table of Contents

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Ph.D. Thesis, 2002 Birte Røgen

Preface

First of all, I thank my supervisor Associate Professor Ida L. Fabricius for her commitment in my project both as research and as a learning process. I thank Birte Brejl, Kirsten Carlsen, Hector Diaz, Bente Frydenlund, Vibeke Knudsen, Flemming Kragh and Sinh Hy Nguyen at DTU for assistance with sample preparation, chemical analyses, imaging and graphical layout. For financial support I thank the Danish Energy Research, Inge Lehmann's Legat af 1983, Joint Chalk Research V and the Nordic Energy Research Council. I also acknowledge the companies who have kindly provided samples and data: Amerada Hess A/S, Mærsk Olie og Gas AS and Phillips Petroleum Company Norway. I thank Professor Gary Mavko, Research Associate Manika Prasad and Research Associate Tapan Mukerji for their supervision during my visit at Department of Geophysics at Stanford University in the fall of 2000. I also thank Professor Rune Holt and Ph.D. student Angelamaria Pillitteri Gotusso for access to laboratory facilities and supervision during my visit at NTNU Norges teknisk-naturvitenskapelige universitet in May 2001.

I thank my colleagues at the department for creating a pleasant and inspiring environment in which I have enjoyed working.

A sincere thank to my family for their patience and support. Particularly, I am grateful to Peter, Rasmus and Rebecca for filling my life with joy and happiness and for their unquestionable love.

Birte Røgen, 2002

Ph.D. Thesis, 2002 Birte Røgen

Ph.D. Thesis, 2002 Birte Røgen

Summary

North Sea chalk
- textural, petrophysical and acoustic properties

The focus of this Ph.D. project has been to investigate the impact of chalk texture on the physical properties of the chalk. The point of view has been a technical one, viewing the chalk as a physical system of solids and pore space, without looking into the geological background of the chalk. Yet, it has been necessary to learn about the geology of the chalk to be able to understand the variety of possible chalk textures. The texture of the chalk is determined by the available material (calcite or silica nanno- and micro fossils and terrigenous material), the depositional processes and the diagenetic alteration. The textural influence was discussed from calcite content, specific surface area, grain size distribution and mineralogy of insoluble residue.

The studied chalk samples originate from seven hydrocarbon chalk fields in the Danish and Norwegian sector of the North Sea. In order to secure a study of the chalk frame and not of fractures and other inhomogeneities the samples have been carefully selected after visual inspection and an extensive quality control of data was performed. Samples have been selected under two projects: Chalk Rock Catalogue: Project 4 under the Joint Chalk Research Phase V and Rock Physics of Chalk under the Danish Energy Research Programme EFP-98. In the sample selection a large variation in porosity and permeability was searched.

The grain size distribution of the chalk samples was obtained by image analysis of electron micrographs. In order to do so an image analysis procedure was developed which is documented in the paper [1]: "Grain size distributions of chalk from image analysis of electron micrographs". The result of the image analysis is a size distribution of the cross sectional area of the grains. The use of two magnifications substantially reduces the number of needed image fields by the assumption of a homogeneous matrix. For 19 samples from the Ekofisk Formation in one field it is observed that the porosity is inversely correlated to the proportion of large grains.

The manuscript [2]:"Ultrasonic velocities of North Sea chalk samples – influence of porosity, fluid content and texture" holds a detailed study of 56 chalk samples from two Danish hydrocarbon fields. The velocity was measured on all samples in dry state, and on 32 samples in water saturated state. Fluid substitution by Gassmann's relations was tested and found to give good estimates of velocities. The ratio between compressional and shear wave velocities was investigated. It was concluded that porosity is the main factor controlling the ultrasonic velocity of the samples and that influence of large grains and clay minerals can be detected on the ultrasonic velocity as secondary factors.

Samples with smectite appear softer than samples with kaolinite, even for samples with calcite content above 95%. This led to a more detailed study of the mineralogy and the specific surface of the insoluble residue in the paper [3]: "Influence of clay and silica on permeability and capillary entry pressure of chalk reservoirs in the North Sea". Here it is documented how permeability and capillary entry pressure of chalk are controlled by porosity and specific surface. The specific surface is primarily governed by the fine grained non-carbonate fraction. This indicates that the low permeability and high capillary entry pressure for a given porosity, which is commonly noted for Ekofisk Formation samples compared to Tor Formation samples, is a reflection of the specific surface area as governed by the insoluble residue rather than the size of the carbonate particles. A model for specific surface of chalk is established and specific surface areas of individual minerals estimated as [m^2/g]: calcite between 0.5 and 3.5, quartz about 5, kaolinite about 15 and smectite about 60.

Prediction of velocity in chalk is tested in the manuscript [4]: "Velocity predictions tested for North Sea chalk: fluid substitution and v_S estimates". Different theoretical, heuristic and empirical methods have been suggested in the literature for shear wave velocity estimation or fluid substitution on compressional velocity alone. We conclude that the empirical method of Castagna et al. (1993) gives good estimates of shear wave velocities. Fluid substitution directly on compressional wave velocities are equally well estimated from the bounding average method, the method of replacing the bulk modulus in Gassmann's relations with the P-wave modulus and the method of decomposing measured P-wave modulus into a shear and a bulk modulus.

In the last manuscript [5]: “Textural influence on ultrasonic velocity of North Sea chalk” the focus has been on the textural influence on compressional velocities because it was shown in [4] that shear wave velocities can be estimated from compressional velocities. The grain size distributions from [1] have been applied to divide the samples into classes of uniform sorting. It was suggested not to concentrate on total amount of insoluble residue because of the result from [3] that it is the clay mineralogy that determines the specific surface more than anything. Here it was observed that samples with more than 4% clay have a distinct lower P-wave modulus-porosity relationship compared to samples with low clay content. For the samples with low clay content poor sorting caused by large grains also gives reason to low modulus-porosity relationship. The observed effect on modulus-porosity relationship of poor sorting is larger for the samples with clay than for samples with large grains. For well sorted samples with low content of both clay and large grains an effect of mineralogy of clay can be observed on the modulus-porosity relationship like it was observed in [2].

Finally two technical notes are included in this thesis. [6] investigates anisotrophy, and finds no anisotrophy for the tested 15 North Sea chalk samples. In [7] no dispersion between ultrasonic measurements performed at 0.7, 1 and 5 MHz can be observed.

Dansk resume

Nordsø-skrivekridt
- teksturelle, petrofysiske og akustiske egenskaber

Fokus i dette Ph.D.-projekt har været at undersøge indflydelsen af kalks tekstur på de fysiske egenskaber af skrivekridt. Angrebsvinklen har været teknisk, hvor kalken ses som et fysisk system af fast stof og porerum, uden at tage hensyn til kalkens geologiske baggrund. Det har dog været nødvendigt at inddrage noget kalk-geologi for at belyse variabiliteten af mulige kalk-teksturer. Teksturen af kalken er bestemt af materialet til rådighed ved aflejringen (calcit og kisel nanno- og micro-fossiler og terrigent materiale), aflejrings-processerne og den diagenetiske modning. Den teksturelle indflydelse er diskuteret ud fra calcit-indhold, specifik overflade areal, kornstørrelses-fordeling og mineralogi af den uopløselige rest.

Prøvematerialet stammer fra syv olie-gas-felter i den Danske og Norske del af Nordsøen. For at sikre et studie af kalk-matrix og ikke af sprækker og andre inhomogeniteter, er prøverne blevet omhyggeligt udvalgt efter visuel inspektion, og der er udført en omfattende kvalitets-kontrol af data. Prøverne er udvalgt gennem deltagelse i to projekter: Chalk Rock Catalogue: Project 4 under the Joint Chalk Research Phase V og Skrivekridtets akustiske egenskaber under Energi Forsknings Programmet (EFP-98). Ved prøveudvælgelsen var der søgt stor variation i porositet og permeabilitet.

Kornstørrelses-fordelingen for kalkprøverne blev lavet ved billed-analyse af elektron-mikroskop billeder. For at gøre dette blev der udviklet en billed-analyse-procedure som er dokumenteret i artikel [1]: "Grain size distributions of chalk from image analysis of electron micrographs". Resultatet af billedanalysen er en størrelses-fordeling af kornenes tværsnits-areal. Anvendelsen af to forstørrelser reducerer antallet af nødvendige billedfelter betydeligt, ved antagelsen om at matrix er homogen. For 19 prøver fra Ekofisk formationen i et felt er det observeret at porøsiteten er omvendt korreleret til andelen af store korn.

Manuskriptet [2]:"Ultrasonic velocities of North Sea chalk samples – influence of porosity, fluid content and texture" indeholder et detaljeret studie af 56 kalk-prøver fra to danske oliefelter. Hastigheden er målt på alle prøver i tør tilstand, og på 32 prøver i vandmættet tilstand. Fluid substitution med Gassmann's relationer er tested og fundet til at give gode estimater af hastigheden. Det er konkluderet at porøsiteten er den styrende faktor for lydhastighed af prøverne og at indflydelse af store korn og lermineraler kan detekteres som sekundær faktor på lydhastigheden.

Prøver med smectit fremtræder blødere end prøver med kaolin, selv for prøver med over 95% calcit. Dette ledte til at mere detaljeret studie af mineralogien og den specifikke overflade af den uopløselige rest i artiklen [3]: "Influence of clay and silica on permeability and capillary entry pressure of chalk reservoirs in the North Sea". Her er det dokumenteret hvordan permeabilitet of kapillar tærskeltryk er styret af porøsitet og specifik overflade. Den specifikke overflade er primært styret af den finkornede ikke-calcit fraktion. Dette indikerer at den lave permeabilitet of høje kapillare tærskeltryk for en given porøsitet, som ofte er noteret for Ekofisk formationen sammenlignet med Tor formations-prøver, er en reflektion af det specifikke overflade areal som er styret af den uopløselige rest i stedet for størrelsen af carbonat partiklerne. Der er opstillet en model for den specifikke overflade af kalken, og den specifikke overflade af individuelle mineraler er estimeret til [m^2/g]: calcit mellem 0 5 og 3.5, kvarts omkring 5, kaolin omkring 15 og smectite omkring 60.

Forudsigelse af lydhastighed i kalk er testet i manuskriptet [4]: "Velocity predictions tested for North Sea chalk: fluid substitution and v_S estimates". Forskellige teoretiske, heuristiske og empiriske metoder til shearbølgelydhastighed estimering eller fluid substitution kun på trykbølgers hastighed har været foreslået i litteraturen. Vi konkluderer at den empiriske metode af Castagna et al. (1993) giver gode estimater af shearbølgehastigheder. Fluid substitution direkte på trykbølgehastigheder er lige godt estimeret ved grænse-midlings metoden, metoden hvor volumen-modul i Gassmann's relationer udskiftes med tryk-bølge modul, og metoden hvor målt trykbølge-modul opløses i et shearbølge- og et volumen-modul.

I det sidste manuskript [5]: "Textural influence on ultrasonic velocity of North Sea chalk" har fokus været på den teksturelle indflydelse på trykbølge hastigheder fordi det var vist i [4] at shear-hastigheder kan estimeres fra tryk-bølge hastighed. Kornstørrelses-fordelingerne fra [1] er anvendt til at dele prøverne i klasser af ens sorteringsgrad. Det er foreslået at undlade at koncentrere sig om andelen af uopløselig rest fordi resultater fra [3] at det er ler mineralogien der bestemmer specifik overflade mere end noget andet. Her er det observeret at prøver med mere end 4% ler har markant laverer trykbølge modul-porøsitets-relation sammenlignet med prøver med lavt lerindhold. For prøver med lavt lerindhold giver dårlig sortering der skyldes store korn også anledning til lavt modul-porøsitet relation. Den observerede effekt af dårlig sortering fra lerindhold på modul-porøsitets relationen er større end effekten fra store korn. For velsorterede prøver med lavt indhold af både ler og store korn kan der observeres en effekt på modul-porøsitets-relationen som det også var observeret i [2].

Til slut er to tekniske noter inkluderet i denne afhandlling. I [6] undersøges anisotropi, og jeg finder ingen anisotropi for de undersøgte 15 Nordsø-prøver. I [7] kan der ikke observeres dispersion mellem lydmålinger foretaget ved 0.7, 1 og 5 MHz.

[6]

Røgen, B. 2002. Anisotrophy in 5 MHz measurements. *Technical note*. Environment & Resources DTU, Technical University of Denmark.

ANISOTROPY IN 5 MHz VELOCITY MEASUREMENTS ON CHALK SAMPLES

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INTRODUCTION

To test whether sonic velocities measured on vertical and horizontal chalk plugs are comparable an anisotropy test was performed on 15 chalk samples. Samples were selected from the Dan, Ekofisk, South Arne, Tyra, Valdemar and Valhall fields covering the Ekofisk, Ekofisk tight, Tor and Tuxen Formations of the Chalk Group in the North Sea. The porosity of the samples range from 20% to 50%. Both compressional (v_P) and shear wave (v_S) velocities were measured.

DATA

Salt and hydrocarbons were cleaned from samples by Soxhlet extraction with methanol and toluene respectively. Samples were dried at 110 deg.C and stored for months under room conditions. From oriented core samples small samples were cut by handsaw and polished to obtain plane and parallel end surfaces both in the vertical and the horizontal direction. The samples were approximately 6 mm thick with an approximate quadratic cross sectional area slightly larger than the transducers (circular, 4 mm in diameter).

The sample is placed between two transducers (broad banded Panametrics 5.0 MHz P-wave or S-wave transducers respectively) with thin plastic foil and Vaseline as coupling substance. The sender transducer is connected to a pulse generator (WAVETEK model 278, 12 MHz programmable synthesized function generator) with an amplifier (ENI model 2100L RF POWER AMPLIFIER). The receiver transducer is connected to a digital oscilloscope (YOKOGAWA DL 1300A), and the digitized transmitted wave is saved in the connected computer. The travel time of the transmitted wave is read manually as first break at the time of measurements. Six plexiglas samples with thickness in the range 2 mm to 20 mm were measured for determination of system delay time.

Standard deviation of velocity is estimated by error propagation where the square of standard deviation (s) equals the variance (V) and f is any function of the two variables x and y (Eq.1). Velocity (v) is calculated from sample size (d), measured travel time (t) and travel time delay (delay) (Eq.2). When Eq. 1 is applied on Eq. 2 we obtain Eq. 4 with Eq. 3 as a calculation. The standard deviation of sample size (s(d)) is estimated to 0.1 mm and the standard deviation on travel time is estimated to 0.1 µs.

$$V(f(x,y)) \cong V(x)\cdot\left(\frac{\delta f}{\delta x}\right)^2 + V(y)\cdot\left(\frac{\delta f}{\delta y}\right)^2 \tag{1}$$

$$v = \frac{d}{t-\text{delay}} \tag{2}$$

$$V(v) \cong V(d)\cdot\left(\frac{\delta v}{\delta d}\right)^2 + V(t)\cdot\left(\frac{\delta v}{\delta t}\right)^2 \tag{3}$$

$$(s(v))^2 \cong V(d)\cdot\left(\frac{1}{t-\text{delay}}\right)^2 + V(t)\cdot\left(\frac{-d}{(t-\text{delay})^2}\right)^2 \tag{4}$$

RESULTS

The measured velocities of the chalk samples fall in the range 1.9-4.6 km/s for v_P and in the range 1.2-2.8 km/s for v_S. We observe that vertical velocities correspond with horizontal velocities within the estimated error for both v_P and v_S (Figure 1).

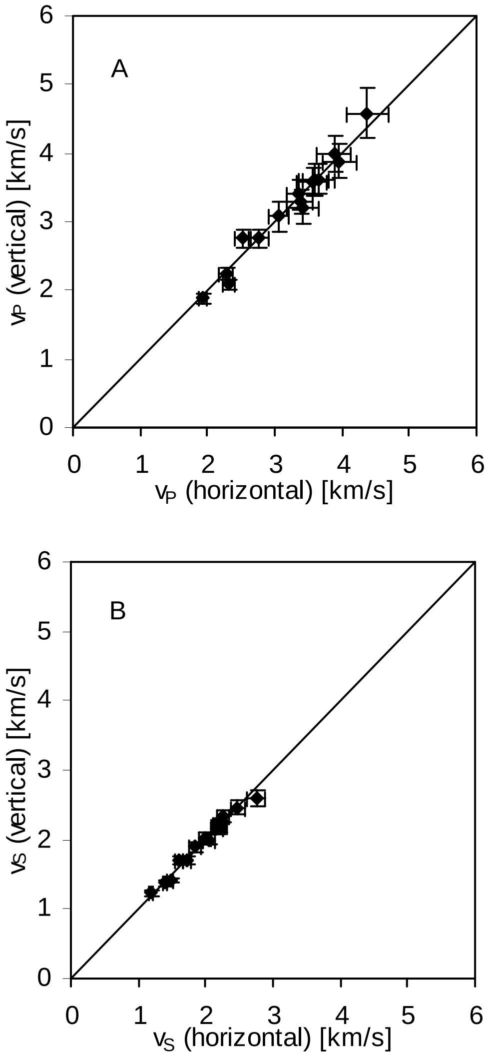

Figure 1. Crossplot of vertical and horizontal velocities for 15 chalk samples with estimated error. A: Compressional velocities (v_P). B: Shear wave velocities (v_S).

CONCLUSIONS

The ultrasonic velocity of 15 chalk samples was measured in vertical and horizontal direction. Within the estimated error the two measured velocities correspond for both compressional and shear velocities. It can be concluded that we observe no velocity anisotropy in the tested samples from six hydrocarbon chalk fields in the North Sea.

[7]

Røgen, B. 2002. Dispersion: 0.7 MHz, 1 MHz and 5 MHz measurements. *Technical note*. Environment & Resources DTU, Technical University of Denmark.

VELOCITY DISPERSION IN NORTH SEA CHALK: 0.7 MHz, 1 MHz AND 5 MHz MEASUREMENTS

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INTRODUCTION

In this note I compare velocities measured on chalk samples at three ultrasonic frequencies. Compressional velocity (v_P) and shear wave velocity (v_S) was measured on 81 North Sea chalk samples with 5 MHz data and 1 and/or 0.7 MHz data. The samples come from Dan, Ekofisk, Gorm, South Arne and Tyra fields both from the Tor and Ekofisk Formations. The samples have a porosity between 22% and 45%.

DATA

Preparation of samples

Salt and hydrocarbons were cleaned from samples by Soxhlet extraction with methanol and toluene respectively. Samples were dried at 110 deg.C and stored for months under room conditions. For the 0.7 MHz measurements 1½ inch plugs were used. For the 1 MHz measurements samples of different sizes were used: 1½ inch plugs, 1 inch plugs or cubes with side length of 1-2 cm. For the 5 MHz measurements smaller samples were prepared: from oriented core samples small vertical samples were cut by handsaw and polished to obtain plane and parallel end surfaces. The samples were approximately 6 mm thick (3.5 mm – 9 mm) with an approximate quadratic cross sectional area slightly larger than the 5 MHz transducers (circular, 4 mm in diameter).

Ultrasonic measurements on chalk samples

5 MHz

The sample is placed between two transducers (broad banded Panametrics 5.0 MHz P-wave or S-wave transducers respectively) with thin plastic foil and

Vaseline as coupling substance. The transducers are fixed in a caliper gauge to obtain contact and determine sample size. The sender transducer is connected to a pulse generator (WAVETEK model 278, 12 MHz programmable synthesized function generator) with an amplifier (ENI model 2100L RF POWER AMPLIFIER). The receiver transducer is connected to a digital oscilloscope (YOKOGAWA DL 1300A), and the digitized transmitted wave is saved in the connected computer. The travel time of the transmitted wave is read manually as first break at the time of measurements. Six Plexiglas samples with thickness in the range 2 mm to 20 mm were measured for determination of system delay time. By error propagation standard deviation of v_P and v_S is estimated to be less than 0.1 and 0.05 km/s respectively.

1 MHz

Measurements were performed the same way as 5 MHz measurements but measured on plugs with a diameter of 1 or 1½ inch or cubes with side length of 1-2 cm. To obtain contact an axial force was applied by introduction of a 2 kg weight on top of the transducer (broad banded Panametrics 1.0 MHz P-wave or S-wave transducers respectively). The travel time of the transmitted wave is read manually as first break at the time of measurements. Six Plexiglas samples with thickness in the range 2 mm to 20 mm were measured for determination of system delay time. By error propagation standard deviation of v_P and v_S is estimated to be less than 0.1 and 0.05 km/s respectively.

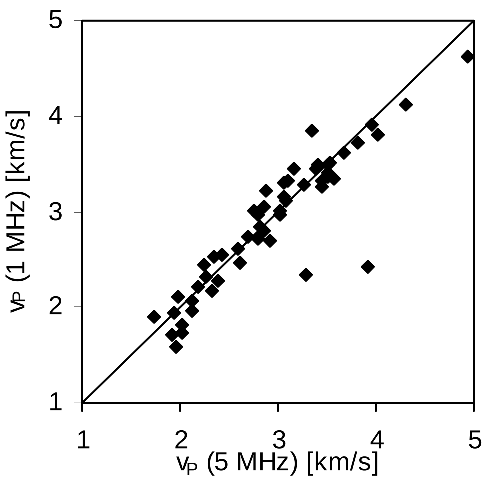
0.7 MHz

Transit times for P- and S-waves were measured on a Tektronix Model TDS3012 2-channel digital-phosphor oscilloscope, connected to a PAR spike-generator and a modified AutoLab 500 Ultrasonic core holder from New England Research. The P- and S-wave transducers have a center frequency of 0.7 MHz. P- and S-wave velocities were measured on each plug under dry conditions at 75 bar hydrostatic confining pressure. The confining pressure was increased gradually in steps of 25 bar during a time period of 30 minutes using a SP-5400 high-pressure pump system from Quizix. The P- and S-wave data were saved digitally for later automated analysis using the arrival picker software of Ødegaard A/S. When unloading the core holder after testing, the confining pressure was decreased gradually from 75 bar to 0 bar during a time period of 1½ hour. The system delay time was determined by measuring transit time without any plugs and on 3 aluminum plugs with different lengths. Standard deviation of sample length, transit time, and density was estimated to

0.1 mm, 0.09 µs, and 0.02 g/cm^2 respectively. Standard deviations of ultrasonic velocities were estimated by error propagation to be less than 0.08 and 0.03 km/s for v_P and v_S respectively.

RESULTS

It can be observed that v_P and v_S measured at both 1 MHz and 0.7 MHz compare with velocities measured at 5 MHz (Figure 1 and 2). Apart from an obvious misfit for three samples in the 1-5 MHz domain, no systematic deviation can be observed. Standard deviation of v_P and v_S is less than 0.1 and 0.05 km/s respectively.



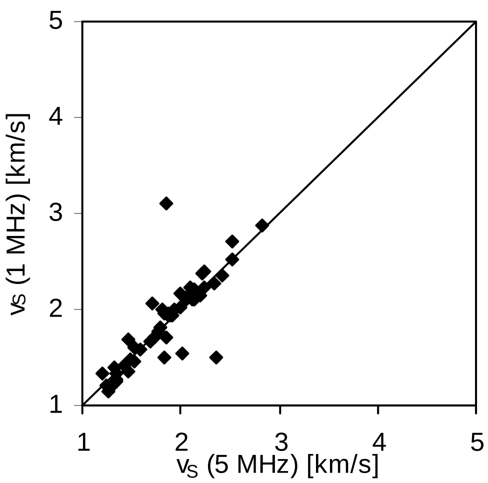
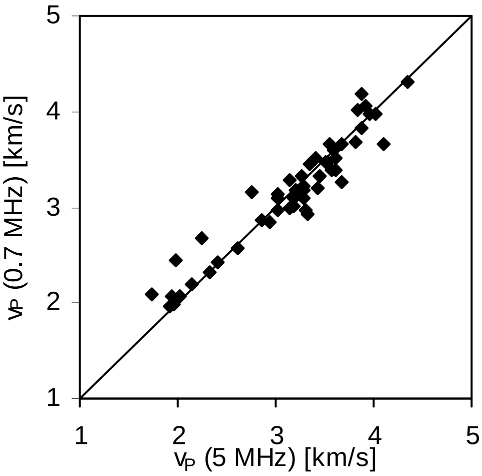


Figure 1. Crossplot of velocity measured at the frequencies 5 and 1 MHz for 53 North Sea chalk samples. Left: Compressional velocities. Right: Shear wave velocities.



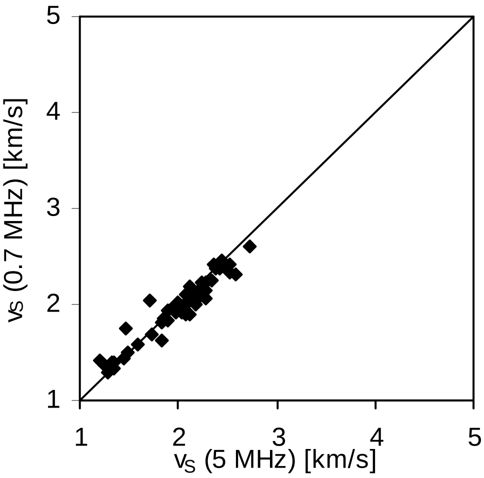


Figure 2. Crossplot of velocity measured at the frequencies 5 and 0.7 MHz for 53 North Sea chalk samples. Left: Compressional velocities. Right: Shear wave velocities.

CONCLUSIONS

For North Sea chalk velocities measured at the ultrasonic frequencies 0.7, 1 and 5 MHz are comparable. It can be concluded that within the ultrasonic frequencies 0.7 to 5 MHz no velocity dispersion can be observed for the studied North Sea chalk from the Tor and Ekofisk Formations with porosity between 22% and 45%.

ACKNOWLEDGEMENTS

Measurements at 1 MHz and 5 MHz were performed by Birte Røgen at NTNU, and financed by the Nordic Energy Research. The 0.7 MHz measurements were performed under the project “Rock Physics of Chalk” financed by the Danish Energy Research Programme (EFP-98) where measurements were performed by Christian Høier at the GEUS Core laboratory.